

Systems of Galaxies in the SDSS: the fundamental plane

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ABSTRACT

We analyse a subsample of the galaxy groups obtained by Merchán & Zandivarez (2005) from the SDSS DR3 to study the fundamental plane and the mass to light ratio of galaxy groups. We find a fundamental plane given by $L_R \propto R^{1.3} \sigma^{0.7}$. We do not find differences when different dynamical sates or redshift ranges are analysed. We find that the mass to light ratio increases with group mass as $M/L_R \propto M^{0.36}$.

Key words: galaxies: clusters: general — methods: data analysis

1 INTRODUCTION

The study of the early type galaxies has allowed the discovery of a plane in the 3-D space of intrinsic properties of galaxies. This plane is known as the fundamental plane (FP) and is expressed as the relation between luminosity, size and intrinsic kinetic energy (Dressler et al., 1987; Djorgovski & Davis, 1987; Guzmán et al., 1993). From the analysis of the FP, information about physical properties, formation and evolution of systems can be obtained. Moreover, the FP has been extensively used as a distance indicator playing an important role in the determination of the Hubble constant (H_0).

The FP concept has also been extended to other systems such as galaxy clusters. Schaeffer et al. (1993), Adami et al. (1998), Fujita & Takahara (1999) and Fritsch & Buchert (1999) have confirmed the existence of a fundamental plane for these large systems. Another topic to be considered when the FP is analysed is the dynamical state of the sample. Fritsch & Buchert (1999) claim that clusters with less substructures (more relaxed) are the strongest tracers of the FP and suggests that the dispersion around the FP is the result of systems of galaxies with a lower degree of relaxation. Beyond these preliminary results, all these authors agree that a larger sample is necessary to have significant statistical weight.

At present, the largest redshift survey of galaxies is the Sloan Digital Sky Survey (SDSS) DR3. Recently, Merchán & Zandivarez (2005) have identified groups of galaxies in this survey, providing the largest sample of groups. Using a subsample of this group catalogue, the present work studies the fundamental plane of galaxy groups and their mass to light ratio. The outline of this paper is as follows: in section 2, we describe the data sample; in section 3, we briefly describe the set of parameters used to define the fundamental plane, while the fit itself is presented in section 4. The mass to

light ratio analysis is detailed in section 5. We summarise our results and conclusions in section 6.

2 THE DATA SAMPLE

The present work is based on a subsample of the groups identified in the SDSS DR3 by Merchán & Zandivarez (2005). Due to the nature of the present work, a very reliable and homogeneous sample of groups is required. Therefore, we only select those groups with at least 10 members. Since the parameters that define the FP can be sensitive to the selection of the groups centre, we implemented the iterative method described by Díaz et al. (2005), which reduces the contamination by substructure. The final sample (hereafter MZDM sample) consists of 495 groups. The median redshift, 3-D velocity dispersion and number of members are 0.077, 642 km s^{-1} and 14, respectively. The distribution of velocity dispersions shown in the left panel of Figure 1 indicates that our sub-sample includes both low and high mass systems of galaxies.

3 THE SET OF PARAMETERS

3.1 Optical luminosity

The luminosity of a group of galaxies identified within a magnitude-limited galaxy sample needs to be corrected for incompleteness effects. In order to correctly compute the luminosity of each group identified in the MZDM sample we use the method described by Moore et al. (1993). According to these authors, the group optical luminosity is defined by the following expression:

$$L_R = L_g + L_{corr} \quad (1)$$

where

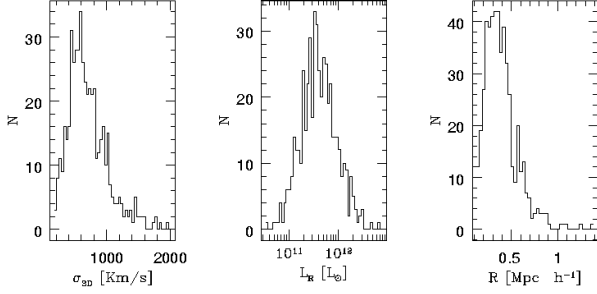


Figure 1. From left to right: distribution of 3-D velocity dispersions, R-band luminosities and radius.

$$L_g = \sum_{i=1}^{N_{gal}} L_i \quad (2)$$

with $L_i = 10^{M_i - M_\odot}$, and

$$L_{corr} = N_{gal} \frac{\int_0^{L_{lim}} L_R \Phi_R(L) dL}{\int_{L_{lim}}^\infty \Phi_R(L) dL} \quad (3)$$

where $L_{lim} = 10^{0.4(M_\odot - M_{lim})}$. $\Phi_R(L)$ is the luminosity function of galaxies in groups. Throughout this work we use luminosities in the R-band.

The absolute magnitudes M_i are calculated using the $k+e$ corrections as a function of redshift, following a method similar to that described by Norberg et al. (2002). This method uses the Bruzual & Charlot (1993) stellar population synthesis code. The luminosity functions of galaxies in groups are estimated following the procedure described by Martínez et al. (2002). Using the complete sample of galaxies in groups identified by Merchán & Zandivarez (2005), we found the following Schechter parameters: $\alpha = -1.00 \pm 0.03$ and $M^* = -20.57 \pm 0.04$. The adopted absolute solar magnitude is $M_\odot = 4.62$ (Blanton et al. 2003). The middle panel of Figure 1 shows the distribution of our group luminosities which extends from $3.41 \times 10^{10} L_\odot$ to $6.94 \times 10^{12} L_\odot$. We adopt an upper limit to the measurement error of 15% in the luminosities as recommended by Adami et al. (1998).

3.2 Velocity dispersions and radius

The velocity dispersion of each group is calculated using the standard technique described by Beers et al. (1990). We apply the biweight estimator for groups with richness $N_{tot} \geq 15$ and the gapper estimator for poorer groups. The median 3-D velocity dispersion for the complete sample of groups is $(642 \pm 190) \text{ km s}^{-1}$. The error in the 3-D velocity dispersion is around of 30% as stated by Beers et al. (1990).

The group characteristic radii is calculated as suggested by Eke et al. (2004a). These authors compute the projected group size using the rms projected physical separation of the galaxies respect to the group centre:

$$R = \sqrt{\frac{\sum_{j=1}^{N_{gal}} d_{jc}^2}{N_{gal}}} \quad (4)$$

where d_{jc} is the projected distance between the centre position and the j^{th} galaxy and N_{gal} is the number of group

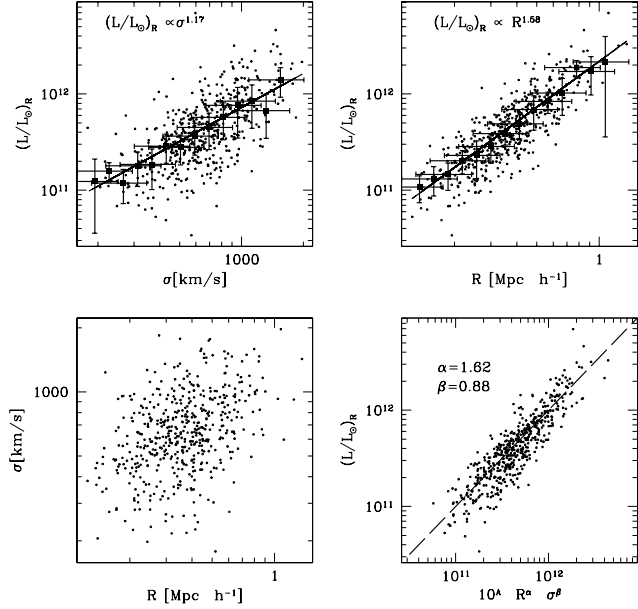


Figure 2. Left upper panel: $L_R - \sigma$ relation. Solid line is the best fit relation. Right upper panel: $L_R - R$ relation. Solid line is the best fit. Filled squares in both panels correspond to the median luminosities per bin of velocity dispersion (left upper) or radius (right upper). Left lower panel: $\sigma - R$ relation. Right lower panel: $L_R - \sigma - R$ relation. The abscissa is $10^A R^\alpha \sigma^\beta$, where A , α and β are the best fit parameters (see text).

members. The right panel of Figure 1 shows the distribution of group radius. The median radii of the sample is $(0.36 \pm 0.10) \text{ Mpc h}^{-1}$. The error in the radius R was estimated using Monte Carlo realisations of mock groups with a given density profile. The procedure takes into account the number of members used to compute the radius and includes uncertainties in the centre position. Considering possible differences between mock and real groups, we adopt a 20% as a conservative upper limit for the error in the groups radius.

4 THE FUNDAMENTAL PLANE

A simple way to start the study of the fundamental plane is by analysing its different projections. Figure 2 shows the $L_R - \sigma$, $L_R - R$ and $R - \sigma$ projections of the FP. As can be appreciated in the left and right upper panels, both, the $L_R - \sigma$ and the $L_R - R$ show a clear correlation in the sense that groups that have large radii or high velocity dispersions tend to be more luminous than those that are smaller or dynamically colder. We fit the $L_R - \sigma$ relation using a method that minimises the sum of the squared weighted orthogonal distances to an analytical curve (or surface). Throughout this work, we perform the fitting procedures using the routines of ODRPACK (Boggs et al., 1992), which takes into account errors in all the coordinates involved. The errors assigned to each coordinate are: $\epsilon_L/L = 0.15$, $\epsilon_R/R = 0.2$, and $\epsilon_\sigma/\sigma = 0.3$. The best fit is shown in the left upper panel of Figure 2 (solid line). Filled squares are the median luminosities per bin of velocity dispersion, the error associated with

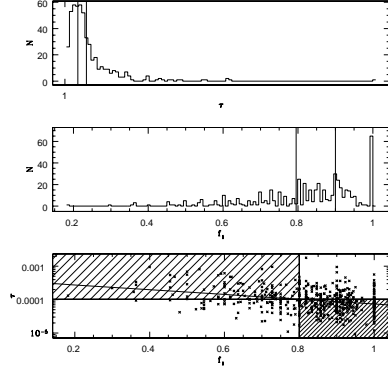


Figure 3. Upper panel: τ distribution. Vertical lines show the τ_1 and τ_2 values. Middle panel: f_1 distribution. Vertical lines are the $frac_1$ and $frac_2$ values. Lower panel: correlation τ vs f_1 . Wide hatched region corresponds to the less evolved groups. Narrow hatched region corresponds to the more evolved groups.

the median is the semi-interquartile range. The best fitting relation is:

$$(L/L_\odot)_R = 10^{b_1} \sigma^{a_1} \quad (5)$$

with $a_1 = 1.17 \pm 0.09$ and $b_1 = 8.35 \pm 0.25$. The right upper panel shows the $L_R - R$ relation, the best fit is:

$$(L/L_\odot)_R = 10^{b_2} R^{a_2} \quad (6)$$

where $a_2 = 1.58 \pm 0.06$ and $b_2 = 12.34 \pm 0.03$.

Left lower panel of Figure 2 shows the projection of the FP in the $R - \sigma$ plane. Larger groups tend to have higher velocity dispersions; however, the correlation is marginal. Due to the poor correlation, the fitting routine does not produce an acceptable relation between radius and velocity dispersion.

Finally, the right lower panel shows the $L_R - \sigma - R$ relation. The fit to the data corresponds to the plane equation

$$(L/L_\odot)_R = 10^A R^\alpha \sigma^\beta \quad (7)$$

The best-fitting parameters given by the ODRPACK sub-routines are: $\alpha = 1.32 \pm 0.06$, $\beta = 0.70 \pm 0.05$ and $A = 10.3 \pm 0.2$.

Even though a good correlation is found, one of the key questions is the origin of the observed dispersion, which could be a consequence of the contribution of groups with different characteristics. Several authors have found that clusters lie in a plane in the 3-D space of $L - \sigma - R$. Nevertheless, they still discuss how the fundamental plane must be defined. Should all the groups lie in the same plane? Or, is the fundamental plane only well defined for groups with some particular physical properties? The assumption of virial state implies that clusters have a constant mass to light ratio, which suggests that groups should lie in a plane defined by $L \propto R\sigma^2$. Nowadays, we know that not all the clusters are virialized, and that the dynamical equilibrium is less common in groups. A more realistic determination of the dynamical state of groups is thus necessary. The size of our group sample gives us a unique opportunity to test whether group dynamical state is one of the factors responsible for the observed dispersion.

The dynamical state of a group can be studied in dif-

ferent ways. Taking into account the available information, we apply two complementary parameters: a dimensionless crossing time, τ , and the early type fraction in groups, f_1 .

(i) the dimensionless crossing time, used by Hickson et al (1992), reflects the dynamical evolution since it is proportional to the inverse of the number of times that a galaxy could have traversed the group from its formation to the present time. τ is defined by:

$$\tau = H_0 t_c = \frac{400}{\pi} \frac{\Delta}{\sigma} \quad (8)$$

where Δ is the mean projected galaxy separation in a group, and σ is the 3-D velocity dispersion.

(ii) If the morphology of galaxies in groups and clusters are the result of environmental processes that subsequently transform galaxies between different morphological classes, early type galaxies should be more numerous in evolved clusters than in young less evolved systems. The fraction of early type galaxies per group is computed after splitting the galaxy sample into 3 spectral types, following Díaz et al. (2005). The fraction f_1 is: $f_1 = N_1/N$, where N and N_1 group total number of members and the number of early type galaxies, respectively. f_1 should reflect the degree of relaxation of a system.

Neither τ nor f_1 are strongly correlated with the redshift nor with the group mass, which is calculated following Eke et al. (2004a):

$$M = 5 \frac{\sigma^2 R}{G} \quad (9)$$

We study the dependence of the fundamental plane on these dynamical parameters. First at all, we define subsamples according to their corresponding τ values: (1) more evolved: $\tau \leq \tau_1 = 7.6 \times 10^{-5}$, (2) intermediate evolution: $\tau_1 < \tau \leq \tau_2 = 1.26 \times 10^{-4}$, and (3) less evolved: $\tau > \tau_2$. Upper panel of Figure 3 shows the τ distribution. Vertical lines are the τ_1 and τ_2 values. We fit a plane (eq. 7) for each subsample. We find no differences between these planes and the defined by the whole sample. We measure the orthogonal scatter around the FP. This orthogonal scatter quantify the aloofness from the FP. Neither of the 3 subsamples shows differences in the scatters.

We split the group sample into the following subsamples, according to their fraction of early type galaxies : (1) less evolved $f_1 \leq frac_1 = 0.795$, (2) intermediate evolution $frac_1 < f_1 \leq frac_2 = 0.9$, and (3) more evolved $f_1 > frac_2$. The quoted values of $frac_1$ and $frac_2$ were selected in order to have subsamples of similar size. The middle panel in Figure 3 shows the f_1 distribution, and the $frac_1$ and $frac_2$ values. Applying the same analysis used for τ , we find no differences in the fitted FPs as in the orthogonal dispersions for the three different subsamples.

Finally, we seek for a correlation between τ and f_1 . It is shown in the lower panel of Figure 3. It can be seen that the relation is not injective. We perform a linear fit in logarithmic axes which is shown as solid line in the Figure. Then, we combine both parameters to pick up two subsamples, corresponding to the more (narrow hatched region) and less (wide hatched region) evolved groups: (1) $\tau \leq \tau_* = 1.03 \times 10^{-4}$ and $f_1 > f_* = 0.8$, and (2) $\tau > \tau_*$ and $f_1 \leq f_*$. Again, we compute the plane and the orthogonal scatters around

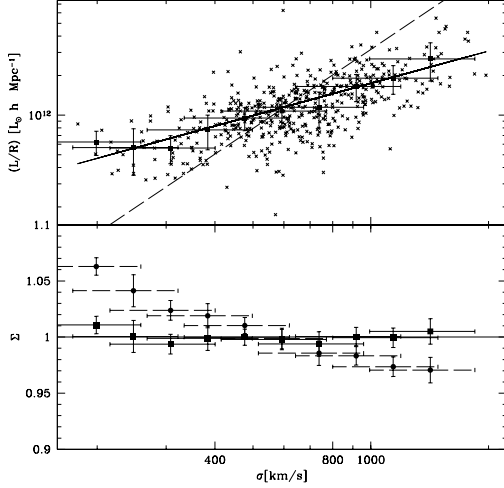


Figure 4. Upper panel: $(L/R) - \sigma$ relation. Filled squares are the median values per bin of σ . Solid line is the best fit to the median data points. Dashed line is the relation expected from the virial equilibrium assumption. Lower panel: Ratios between median values and the linear relations. Filled squares corresponds to best fit, and filled circles are computed with the virial prediction.

the FP for each subsample. The results are the same found before. Both subsamples have the same behaviour.

From the analysis performed in this section, we conclude that, using the parameters τ and f_1 to study the group dynamical state, the fundamental plane does not show signs of evolution.

We also study the dependence of the fundamental plane on the group redshifts. We define 2 subsamples corresponding to the lowest and the highest redshift ranges. The resulting planes have no differences with the FP defined by the whole sample, and the orthogonal scatters around the FP are very similar for both subsamples. However, this result is not conclusive since our sample spans only a small redshift range ($z \leq 0.2$), wherein only minor dynamical evolution is expected.

Finally, in order to show that the fundamental plane expected from the virial assumption is rejected by the MZDM sample, the upper panel of Figure 4 shows the $(L/R) - \sigma$ relation. Solid line is the best fit to the data (filled squares: $(L/R)_{\text{median}}$ per bin of σ), and dashed line is the relation expected when assuming virial state. Lower panel of this Figure shows the ratios between the median values and the linear relations (best fit: filled squares - virial relation: filled circles). It can be seen that the virial relation is not a good description to the observational data.

5 MASS TO LIGHT RATIO

The fact that the FP we measure is different from the one expected assuming virial equilibrium ($L \propto R\sigma^2$) means that the mass to light ratio must vary. Girardi et al. (2000) calculate the $L_B - M$ relation and find that the luminosity has a tendency to increase slower than the mass ($L_B \propto M^{0.75}$). These authors also suggest that this result is independent of

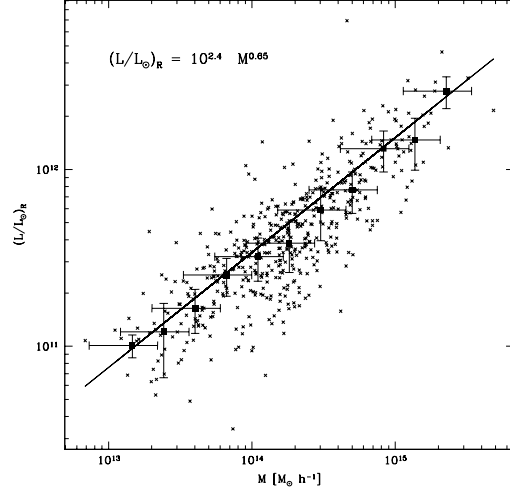


Figure 5. $L_R - M$ relation. Filled squares are the median luminosity per mass bin. Solid line is the best fit.

the photometric band, which was confirmed by Popesso et al. (2004). Figure 5 shows the $L_R - M$ scatter plot (points) corresponding to the complete sample of groups. Filled squares are the median luminosity per bin of mass, errors in the median luminosities are computed as the semi-interquartile range, and the mass errors are computed by error propagation ($\sim 60\%$). Solid line corresponds to the best fit to $L_R = 10^b M^a$, with $a = 0.64 \pm 0.03$ and $b = 2.6 \pm 0.4$. This result is in agreement (within $2\sigma_a$) with the results obtained by Girardi et al. (2000), and it is also comparable (within σ_a) with the results of Popesso et al. (2004). It should be noted that L varies almost linear with σ ($\beta \sim 1$) (quadratic in the virial case), then the M/L ratio must increase with σ , it means with M . Several authors have stated that is not correct to search for the best fitting relation of $M - L$ ratio versus M or L (Eke et al., 2004b, Popesso et al., 2004, Girardi et al. 2002), then it is more suitable to infer the relations from the L vs M directly. Therefore, our previous result implies $M/L \propto M^{0.36 \pm 0.06}$, it means that the mass to light ratio of galaxy groups is not constant, M/L varies up to a factor of ~ 6 from low to high mass groups. The group sample analysed in our work presents a steeper slope of the M/L vs M relation, in comparison with previous works on groups and clusters of galaxies (0.25 ± 0.1 Girardi et al., 2000, Adami et al. 1998; 0.2 ± 0.08 Popesso et al. 2004), but they are in good agreement within 1σ -level. The median mass to light ratio of our sample is $(M/L)_{\text{med}} = (418 \pm 194) M_\odot / L_\odot$.

In order to check the stability of our results against a different choice of the group size, we repeated our analysis using the group standard virial radius and the virial mass provided by Merchán & Zandivarez 2005. The median virial radius of the sample under study is $0.96 \pm 0.20 \text{ Mpc } h^{-1}$. The relation between the virial radius and the radius used in this work is linear ($R_{\text{vir}} = (1.72 \pm 0.02) R + (0.29 \pm 0.01)$) with a small dispersion, but it has a non zero intercept. Then, the fundamental plane fitted using the virial radius slightly differs from the fit derived in the previous section.

The $L - M$ relation does not depend on the definition of the radius or mass. Comparing the orthogonal scatter pro-

Table 1. Fundamental plane and $L - M$ best-fitting parameters for different prescriptions of size parameter and mass.

Prescription	$L = 10^A R^\alpha \sigma^\beta$			FP orthogonal scatter Σ	$L = 10^b M^a$	
	α	β	A		a	b
Eke et al.(2004a)	1.32 ± 0.06	0.70 ± 0.05	10.3 ± 0.2	0.08	0.64 ± 0.03	2.6 ± 0.4
Virial	1.85 ± 0.08	0.73 ± 0.06	9.7 ± 0.2	0.10	0.64 ± 0.04	2.7 ± 0.6

duced by the two different selection of the size parameters, we find that the characteristic radius proposed by Eke et al. (2004a) produces the smaller scatter in both, the fundamental plane and the $L - M$ fits, and it also produces smaller errors in the fitted parameters. Table 1 shows the results corresponding to the two size parameters.

6 CONCLUSIONS

In this work we study whether the more numerous galaxy systems, the galaxy groups, lie in the so-called "fundamental plane", defined by their physical properties. We analyse a subsample of the Merchán & Zandivarez (2005) catalogue of groups (MZDM sample). The use of this large and homogeneous sample allows us to obtain results that are statistically reliable. We find that these groups define a plane given by $L_R \propto R^{1.3} \sigma^{0.7}$ which is different from the plane that is expected if one assumes virial equilibrium. We also analyse the aloofness from the plane as a function of the dynamical state of groups and their redshifts. We find that none subsample has a tendency to lie farther or closer from the FP.

We also find that the mass to light ratio increases with group mass as $(M/L_R) \propto M^{0.36}$. Over the mass range of our sample (two orders of magnitude), the M/L_R ratio increases a factor of ~ 6 from low to high mass systems.

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